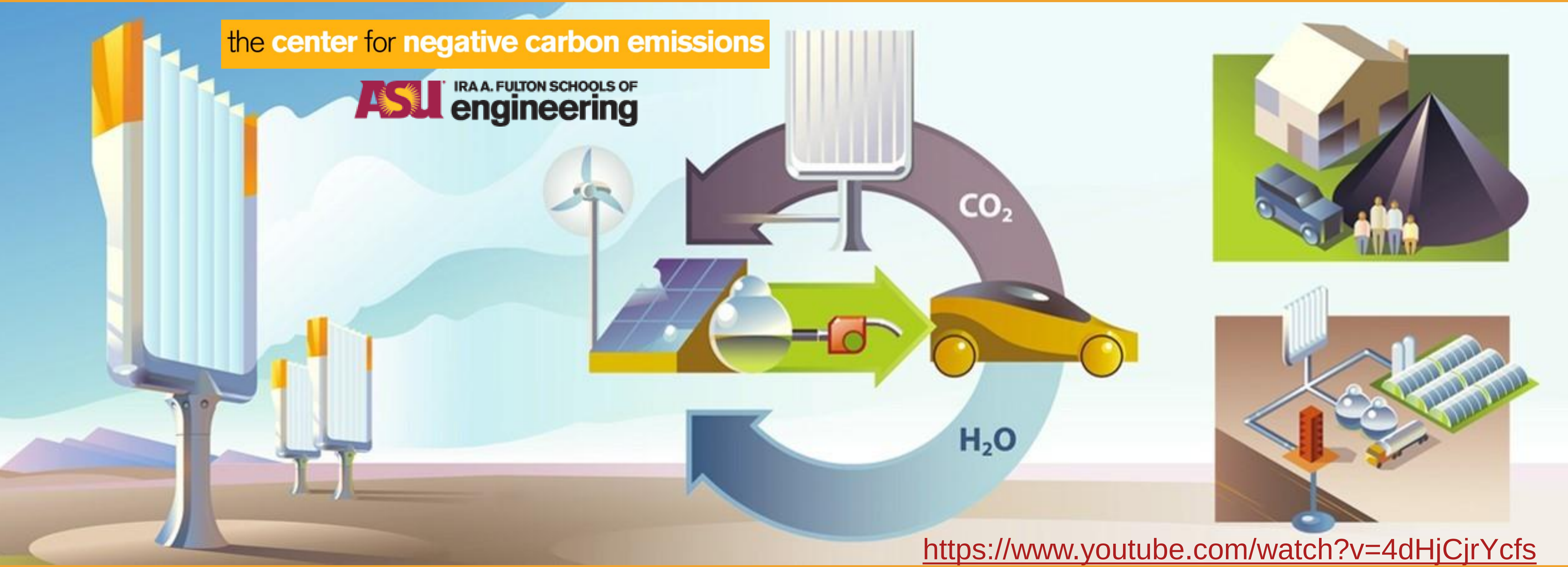
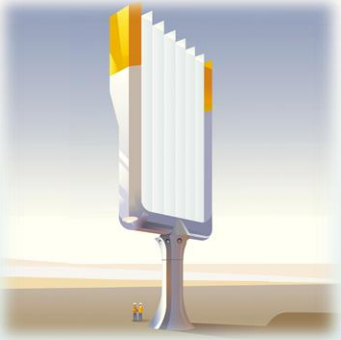


https://www.youtube.com/watch?v=4dHjCjrYcfs

Direct Air Capture and Other Innovative Approaches to CO_2

Klaus S Lackner

March, 2018



The global carbon budget is heading into overdraft

Paris Agreement: hold warming below 1.5°C or at most 2°C

- *Promised emissions reductions will reach 4°C, business as usual more than 6°C*
- *Cannot stop anymore in time*

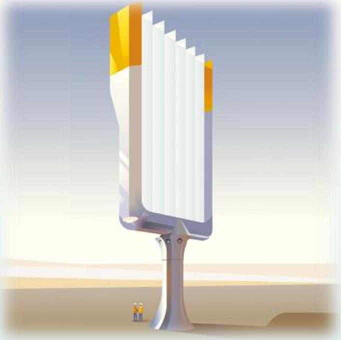
IPCC: need negative emissions

- *Pulling CO_2 back from the air*
- *Storing CO_2 safely and permanently*

Personal Carbon Allowance is less than 30 tons
Total permanent allotment

Carbon constraints pose major risks to the economy, opportunity for those who can fix it

http://www.emercedesbenz.com/Aug08/08_001327_Mercedes_Benz_Econic_Semi_Trailer_Tanker_Trucks_Enter_Service_At_London_Farnborough_Airport.html



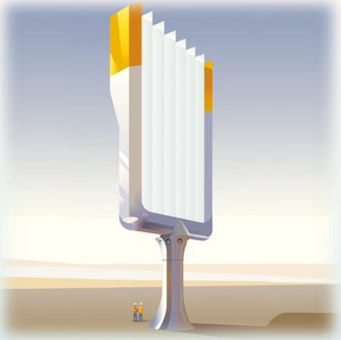
Carbon dioxide piles up like garbage

- Carbon dioxide emissions stay in the atmosphere for centuries
- Warming from carbon dioxide lasts for a millennium
- Excess carbon acidifies the ocean for millennia
- Geological weathering resets carbon on the 10,000 to 100,000 year time scale

- Moving to a waste management paradigm represents a big shift in dealing with CO_2
- Reduce, Reuse, Recycle + DISPOSAL
- Cost of Disposal motivates Reuse
- Zero Waste is a long term goal after cleanup

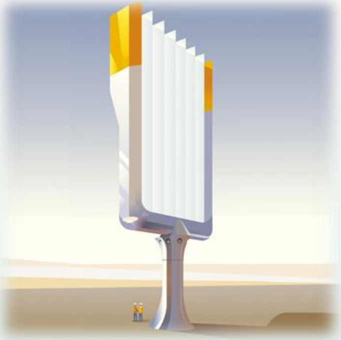
Need to convince people and corporations to clean up their CO_2 garbage

Create a movement like recycling



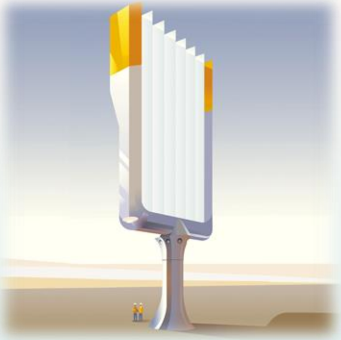
Stuck in a hole? – Stop digging!

- **Capture Emissions at Point Sources (CCS)**
  - Retrofits have proven surprisingly difficult
    - *Old plants are difficult to change*
    - *Large infrastructure for CO_2 transport*
  - Acceptance for novel designs would be politically difficult
    - *20 years ago that might have been an option*
- **Avoid fossil fuels altogether**
  - Cost of renewable energy is dropping fast
  - Intermittency remains an issue
- **Last 20% of emissions are difficult**
  - Peaker plants for power backing up renewables
  - Ships and air planes in the transportation sector
  - Need synthetic liquid fuels (CO_2 + H_2O + sunshine → Fuel)



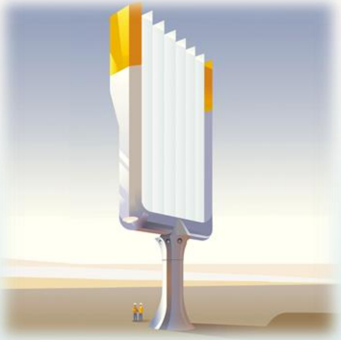
Carbon Cycle must be closed Downcycling is not sufficient

- **CO_2 from fossil power plants is fossil carbon**
  - The captured CO_2 is fossil carbon
  - Needs to go back into the ground
  - Fuels from flue stack CO_2 are still fossil fuels
  - As long as carbon comes out of the ground, CO_2 has to be put back in the ground
  - Once the CO_2 ends up in the environment it needs to be recaptured
- **CO_2 from air plus solar energy can produce sustainable liquid fuels**
  - Biofuels or synthetic fuels



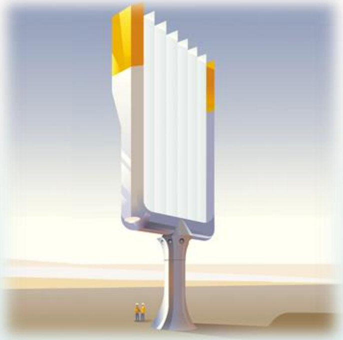
Need for carbon removal or Drawdown Negative Emissions

- Compensating for continued use of fossil fuels
  - Will take decades to stop emissions and phase out fossil fuels
  - We act too slowly, but we can’t go too fast either
- Recovering from an overshoot
  - Return to prior values 350 ppm, 400 ppm, 450 ppm?
  - Prepare for recovering 1 to 2 trillion tons of CO_2
    - *1500 Gt CO_2 ~ 100 ppm (40 years of current emissions)*
    - *More than 20^{th} century emissions*
- Carbon Storage has become unavoidable



Paying back the carbon debt by removing carbon from the environment

- Collection from the biosphere
  - Excellent starting point
    - *Affordable, but fails to scale*
    - *60 years of current emissions = biomass carbon*
    - *Drawdown in 40 years exceeds agriculture*
- Collection from the ocean
  - Dissolved inorganic carbon (DIC)
    - *Readily exchanges with the atmosphere*
    - *Dilution 1 : 25,000*
    - *Large reservoir, but poorly mixed*
- Collection from the air
  - Readily accessible and scalable
    - *Well mixed*
    - *Dilution 1 : 2,500*



Technologies for Carbon Management DACCS and DACCU

- **Carbon Storage**

  Disposal of excess carbon underground

  Established technology but not at scale

- **Fuel Synthesis/Chemicals**

  Converting renewable energy into liquid fuels

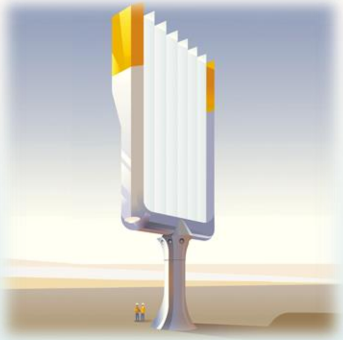
  Producing chemical feedstock from CO_2

  Based on proven technology, needs scaling

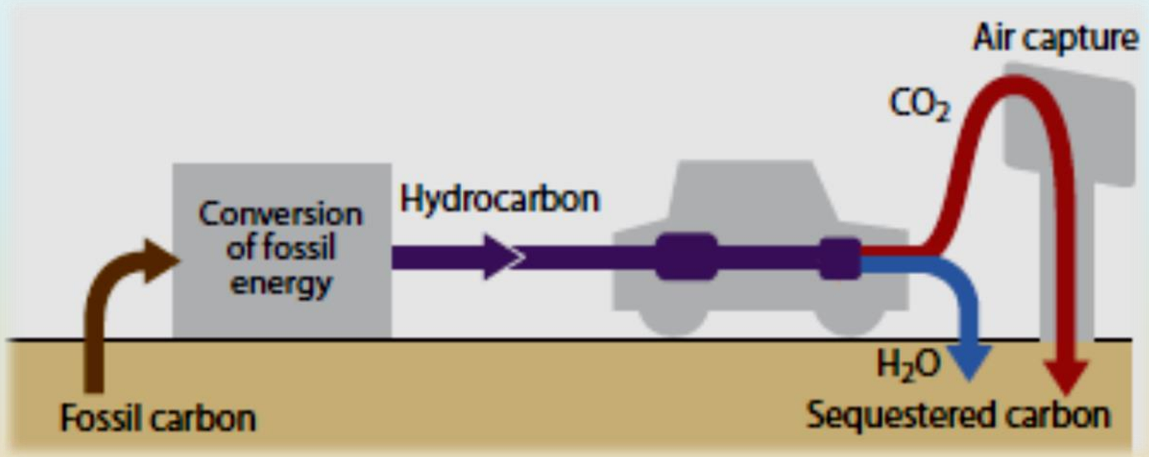
- **Direct Air Capture of Carbon Dioxide**

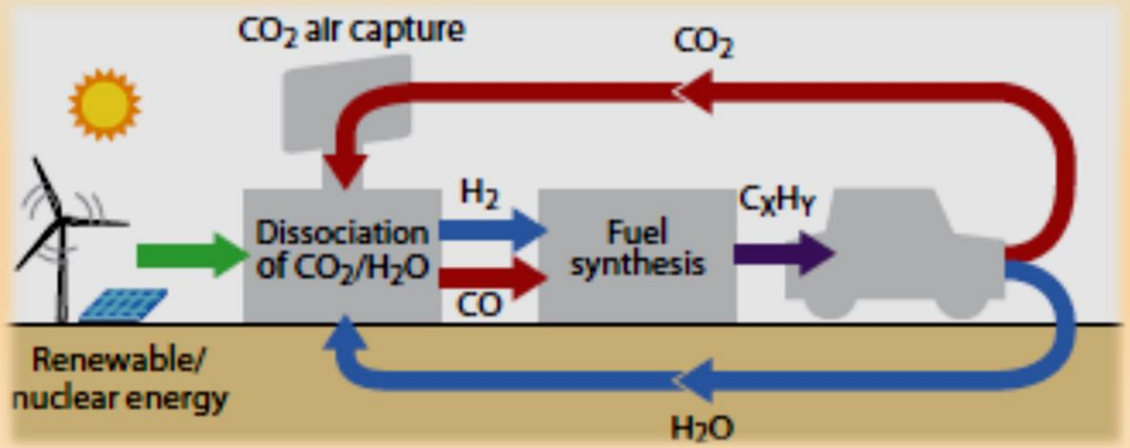
  Novel technology we have introduced

  Needs demonstration and scaling



Direct Air Capture balances the carbon budget through storage or fuel synthesis

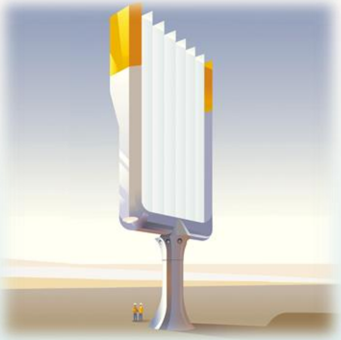




Air capture devices are mechanical trees

- Thousand times faster than natural trees
- Collect current and past emissions
- Deliver CO_2 for disposal or fuel synthesis
- Can operate at global scale
- Air transports CO_2 for free
- No need for pipelines

Markets will determine the balance between different options



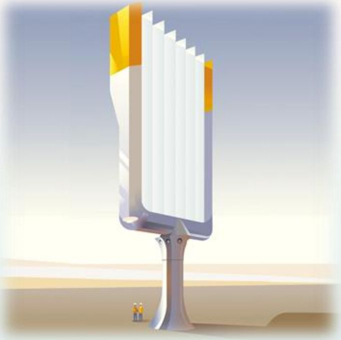
Out of the box thinking

No direct path …

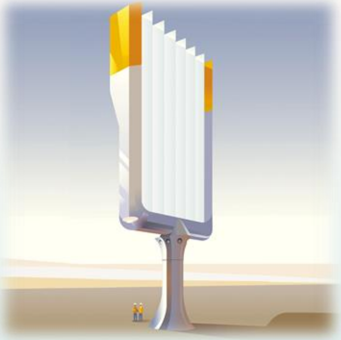
… from here …

… to there

Start from first principles
and
air capture is feasible



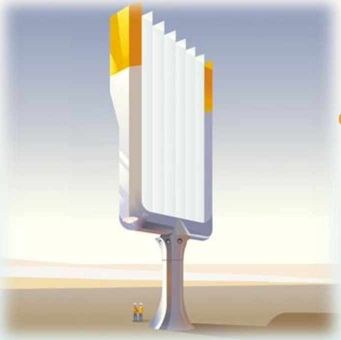
Inspiration comes from nature



CO_2 in the air is not too dilute!

- One cubic kilometer of air
  - Passes through a wind mill in the course of an afternoon
  - Carries $300 of kinetic energy
    - *assuming a wind speed of 6m/s and a value of 5¢/kWh*
  - Carries $21,000 of CO_2
    - *assuming a tipping fee or commodity value of $30/ton*

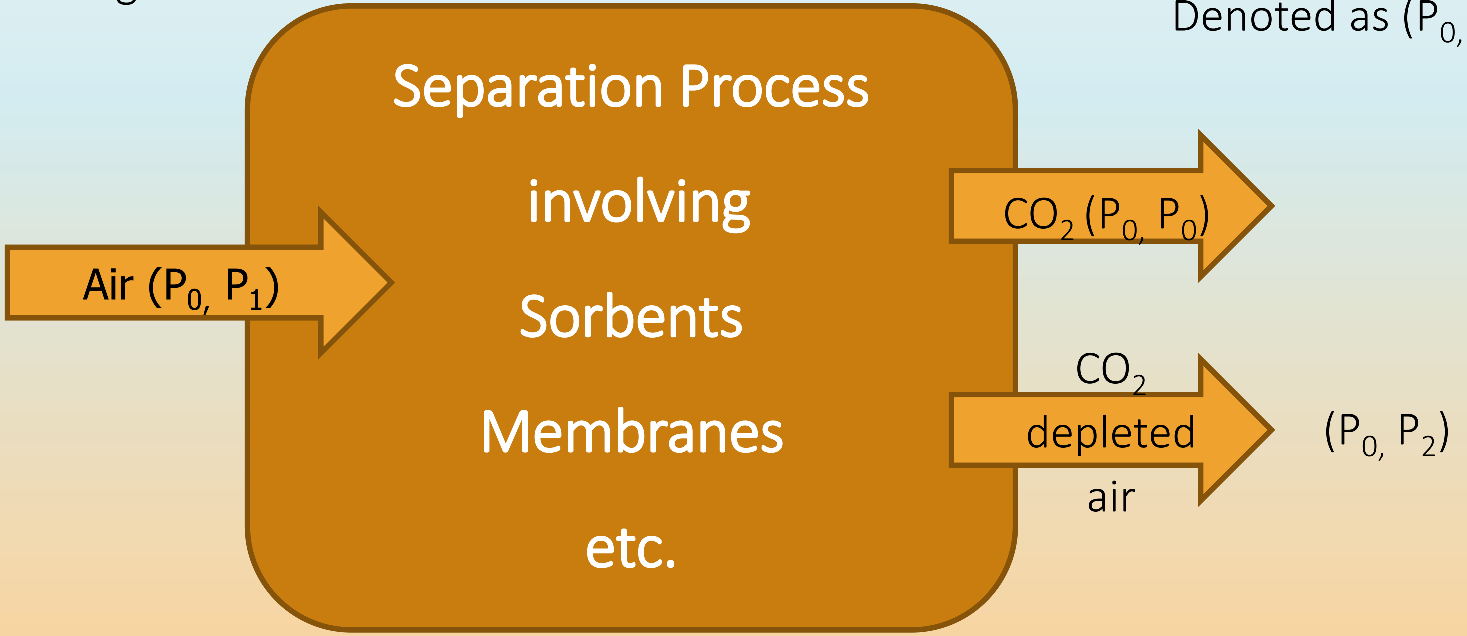
As a source of CO_2, the air is 70 times more valuable than as a source for wind energy.
Wind energy is routinely harvested



Thermodynamics is not limiting

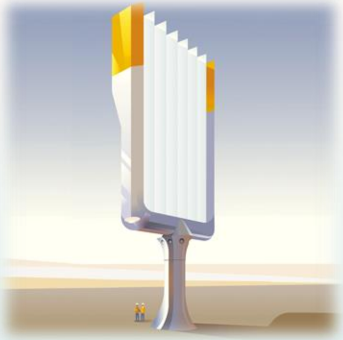
Theoretical minimum free energy requirement for the regeneration is the free energy of mixing

Gas pressure P_0
CO_2 partial pressure P_x
Denoted as (P_0, P_x)



$$\Delta G = RT\left(\left(\frac{P_0 - P_2}{P_1 - P_2}\right)\frac{P_1}{P_0}\ln\frac{P_1}{P_0} - \left(\frac{P_0 - P_1}{P_1 - P_2}\right)\frac{P_2}{P_0}\ln\frac{P_2}{P_0} + \left(\frac{P_0 - P_1}{P_0}\right)\left(\frac{P_0 - P_2}{P_0}\right)\frac{P_0}{P_1 - P_2}\ln\frac{P_0 - P_1}{P_0 - P_2}\right)$$

Specific irreversible processes have higher free energy demands



Avoiding Sherwood's Rule

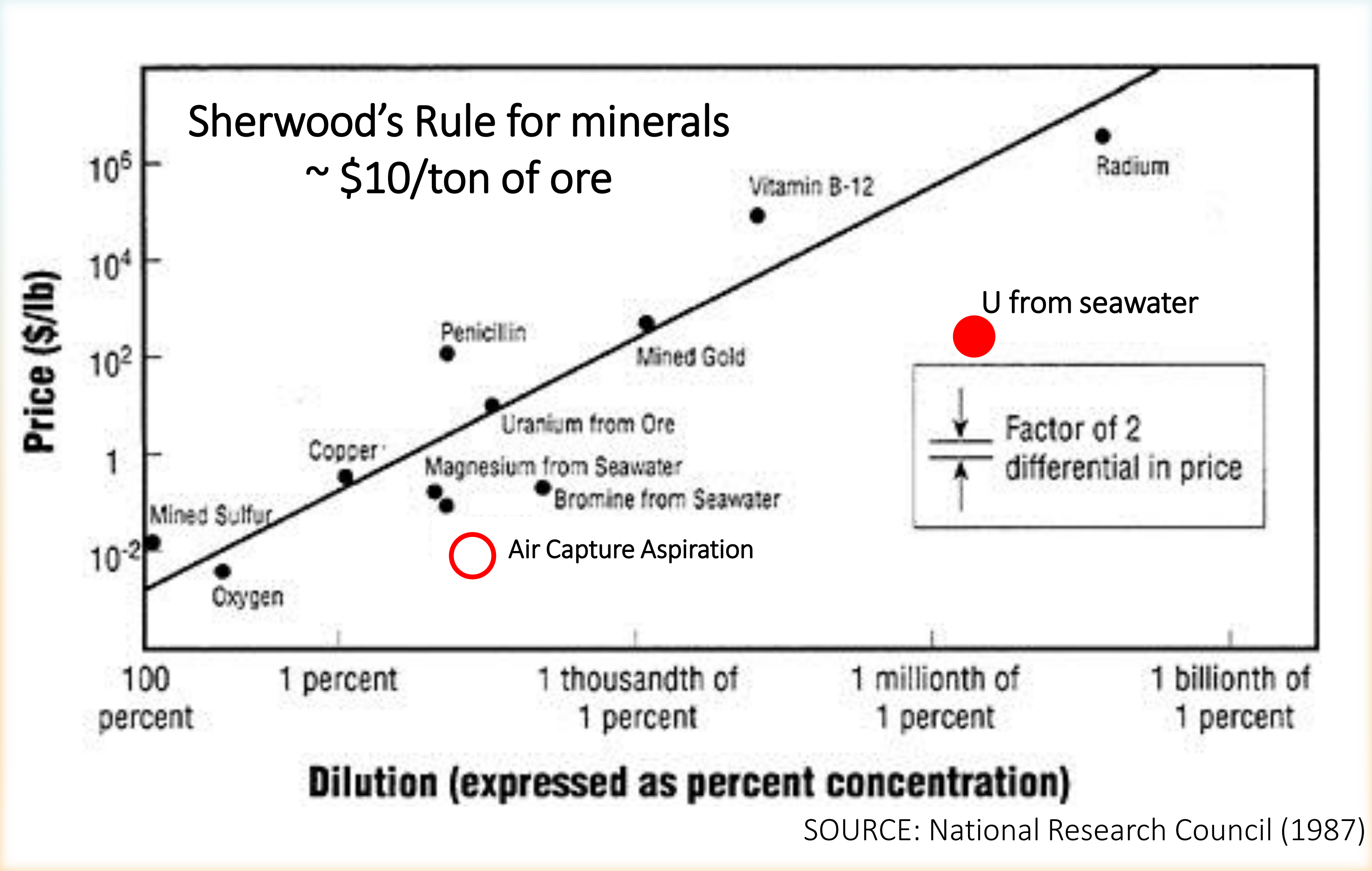
Cost of separation scales linearly with dilution *D*

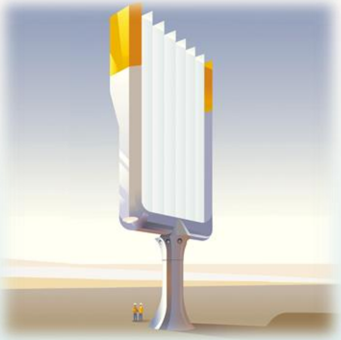
Sherwood's Rule

- The cost of the first step in the separation dominates
- $Cost = aD + b + c\log D$

Bulk processing

Thermodynamic separation





Air Capture can avoid Sherwood's Rule

DAC need not crush or grind air

Dominant cost is sorbent regeneration

somewhat more energetic than flue gas sorbent recovery

Air collector reduces net CO_2 emissions much more than equally sized windmill

Extracting kinetic energy from air at 20 J/m^3 is feasible

Image courtesy Stonehaven production

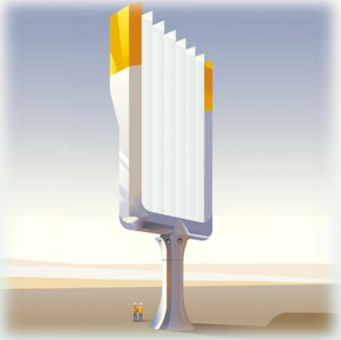
Wind energy ~20 J/m^3

CO_2 combustion equivalent in air

10,000 J/m^3

Contacting of air can be inexpensive

Regeneration cost are slightly larger than for flue gas scrubbing



Air Capture is Real

- Several start-ups have working prototypes
- Different approaches, different markets
- Gaining experience, demonstrating costs
- Establishing a new technology

Carbon Engineering

CLIMEWORKS

globalthermostat

INFINITREE

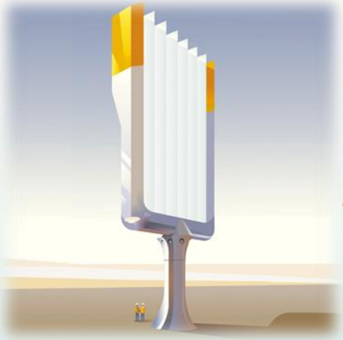
Research is proceeding at a number of universities

ASU, Georgia Tech, Columbia University,

ETH Zurich, Sheffield University, Zhejiang University, …

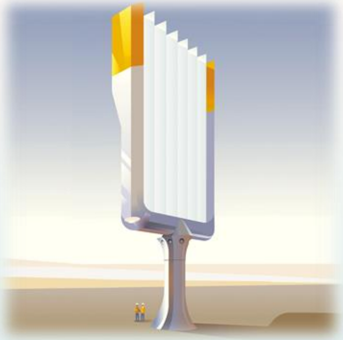
….

Commercial Interest is stirring, carbon price incentives are starting, 45Q Tax Credit in the US is worth $50/ton



ASU's Direct Air Capture

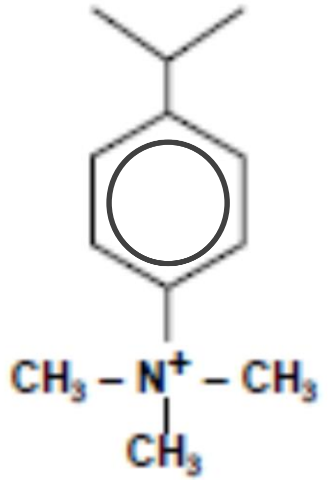
- Passive System
- Moisture Swing Sorbent
- Mass Manufacturing Design
- Two Stage Concentrator



Moisture Swing Sorbent for Low Energy Air Capture

Anionic Exchange Resin: Solid carbonate "solution"
Quaternary ammonium ions form strong-base resin

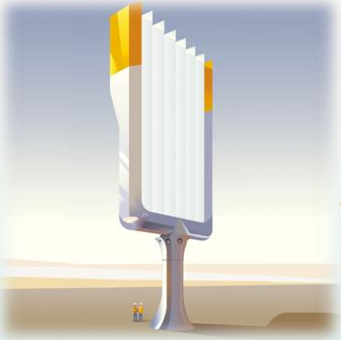
Type I Strong Base Resins



- Positive ions fixed to polymer matrix
  - Negative ions are free to move
  - Negative ions are hydroxides, OH^-

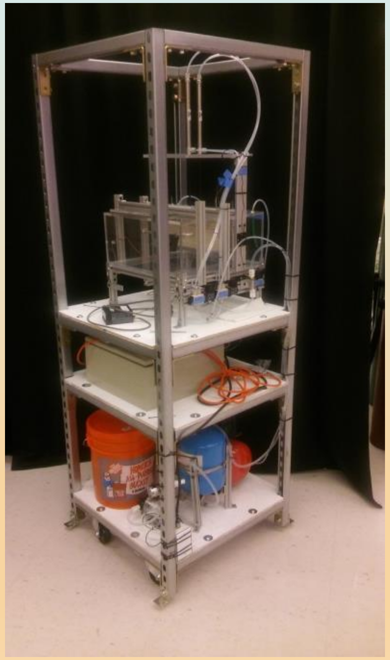
- Dry resin loads up to bicarbonate
  - $OH^- + CO_2 \rightarrow HCO_3^-$ (hydroxide → bicarbonate)

- Wet resin releases CO_2 and unloads to carbonate
  - $2HCO_3^- \rightarrow CO_3^{--} + CO_2 + H_2O$



ASU's air capture design

- Passive wind-driven design avoids Sherwood's objection
- Moisture controlled sorbent reduces energy consumption
- Mass production of small units drives costs down

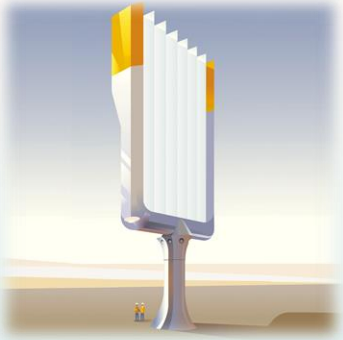


Lessons are applied in a DOE project to feed CO_2 to algae

 Prototype tested on the roof

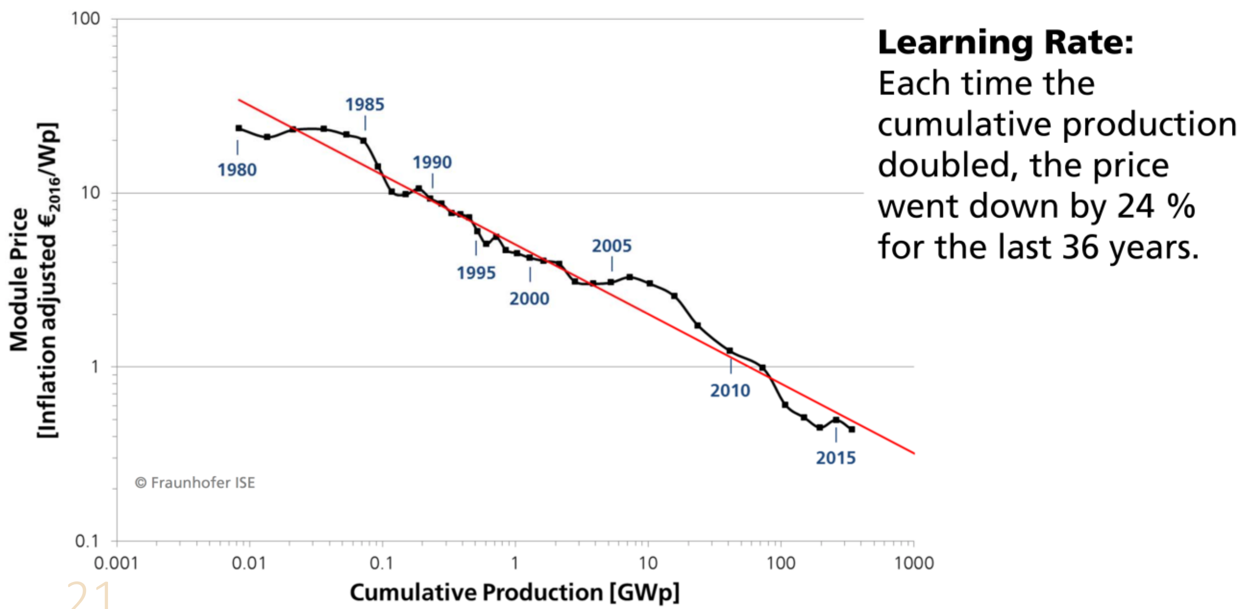
Tiburio™ Design

- **Harvest**
  - Wind flows through gaps between horizontal sorbent disks, disks dry and load up with CO_2
- **Moisture sensitive sorbent**
  - releases CO_2 if exposed to moisture and/or heat
  - First concentration step requires only minimal energy
- **Regeneration**
  - Disks are regenerated through moisture inside the bottom chamber, creating low pressure CO_2 (in air, or in vacuum)
  - Upgrade through innovative evacuation/compression with built-in energy storage
- **Designed for mass-manufacture**
  - One-ton-per-day system



Mass production: A path to scaling up

- Car engines are 100 times cheaper than power plants on a kilowatt basis
  - Mass production wins out over the economy of scales
  - Short life times reduce risks specifically risks of obsolescence
  - Small scales shorten time to deployment
  - Automation addresses cost of operation and maintenance

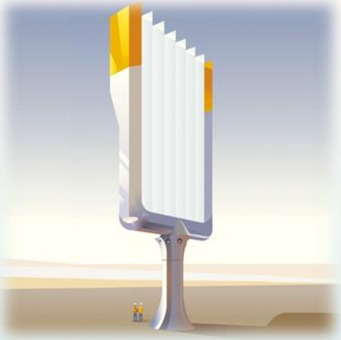


Data: from 1980 to 2010 estimation from different sources : Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011 to 2016: IHS. Graph: PSE AG 2017

- Economies of scale: $C = C_0 \left(\frac{s}{s_0}\right)^{\alpha}, \quad \alpha \sim \frac{2}{3}$
- Economies of numbers: $c(2n) = \varepsilon c(n), \quad \varepsilon \sim 0.8$
- Cost of N small units: $C = \frac{c(1)}{1+\log_2 \epsilon} N^{1+\log_2 \epsilon}$

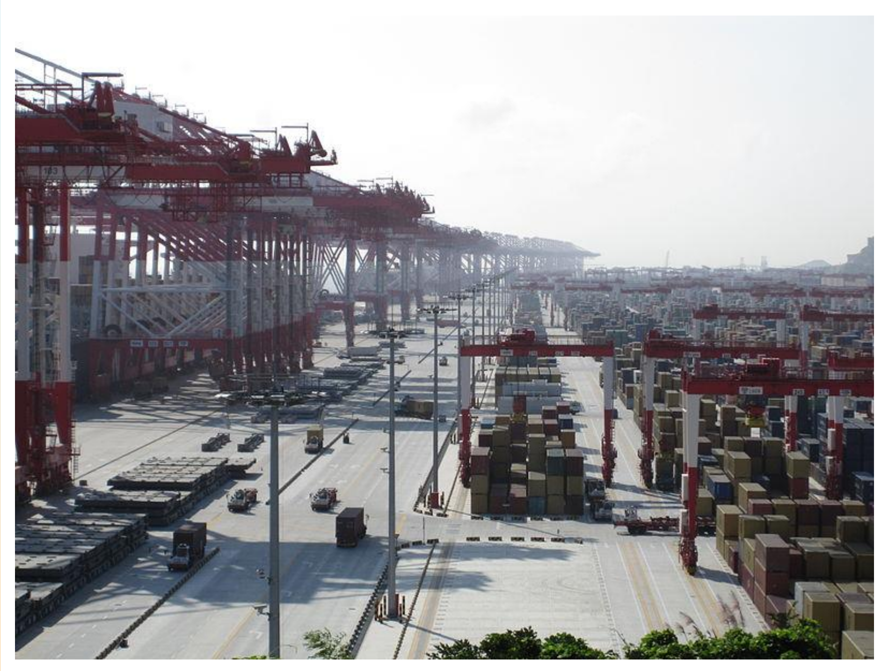
Same Power Law!

Photovoltaic learning curve from “Photovoltaics Report,” Fraunhofer Institute for Solar Energy, Freiburg July 2017



100 million units balance current emissions

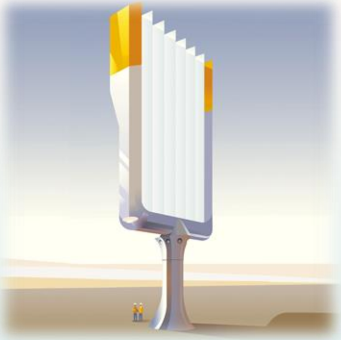
10 year life time implies a production capacity of 10 million per year



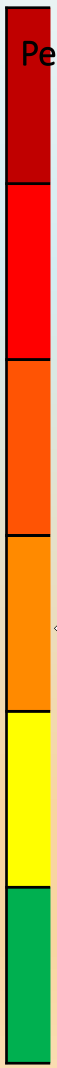
Shanghai harbor processes
30 million full containers a year

World car and light truck production:
80 million per year

wikipedia pictures



Low cost comes with experience

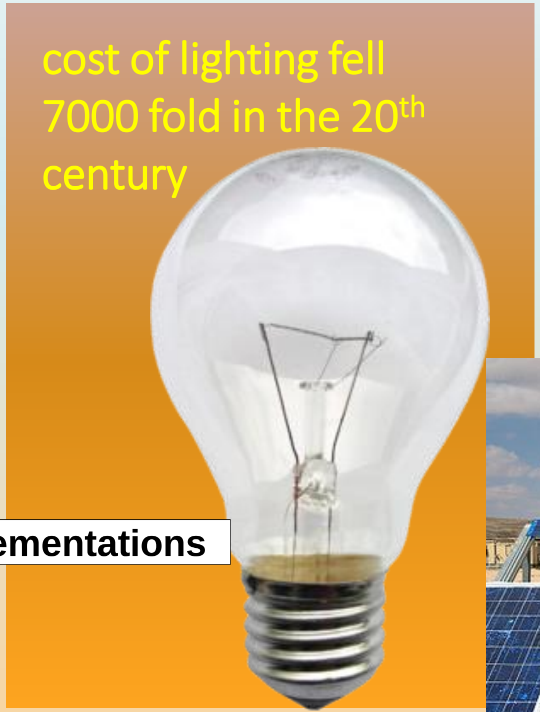


APS (low tech, first-of-a-kind)

Early implementations

Practical interest

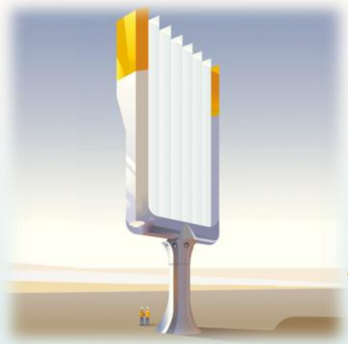
Raw material and energy limit (frictionless cost)



Cost ratio to navigate is much smaller than for renewable energy

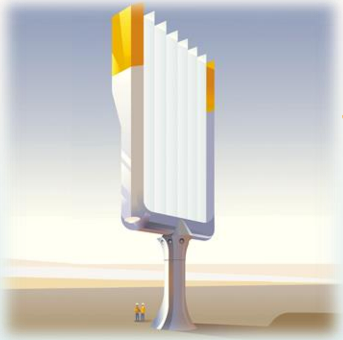
Ingredient costs are already small – small units: low startup cost

Wikipedia pictures



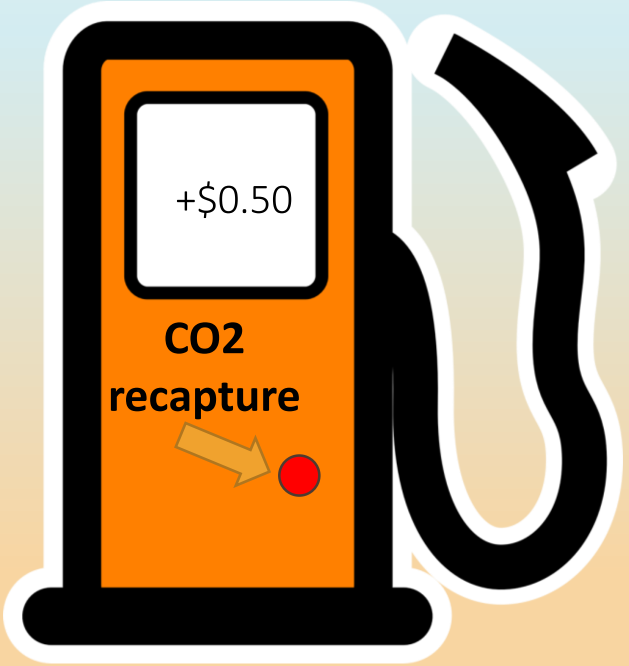
CO_2 emissions require waste management: A utility type activity

- **Waste management is a lucrative service industry**
  - With a profitable sideline in carbon reuse and carbon recycle
    - *CO_2 feedstock for agriculture, oil recovery, synthetic fuels, infrastructure materials*
  - Negative emissions require carbon storage/disposal
    - *Reducing atmospheric CO_2 by 100 ppm creates demand for 1500 billion tons of storage*
- **Worldwide political change will drive a trillion dollar industry**
  - Carbon constraints in the EU
    - *Serious limits on countrywide emissions already drive investment decisions*
  - Carbon credits in the US introduced last week
    - *$35 for capturing a ton of CO_2 from air, plus $35 for its beneficial use or $50 for disposal*



Value Propositions

- Voluntary repayment of carbon debt for individuals and sustainably minded corporations
  - *This is how recycling became a business, how renewable energy is paid for*
  - *Volunteers create a carbon price, regulatory policies will follow*
- Societal license to operate for carbon producers
  - *Without air capture, liquid fuels will have to be phased out*
- Protecting assets in the ground
  - *Natural gas is not running out and a valuable resource*
- New business opportunity around waste management
  - *Waste management for garbage and sewage has been built into lucrative enterprises*
- Reducing future liabilities



Imagine a button at the pump to take back the 20 pounds of CO_2 emitted from a gallon of gasoline